Measurements of Direct Photon Production Cross Sections at the Tevatron

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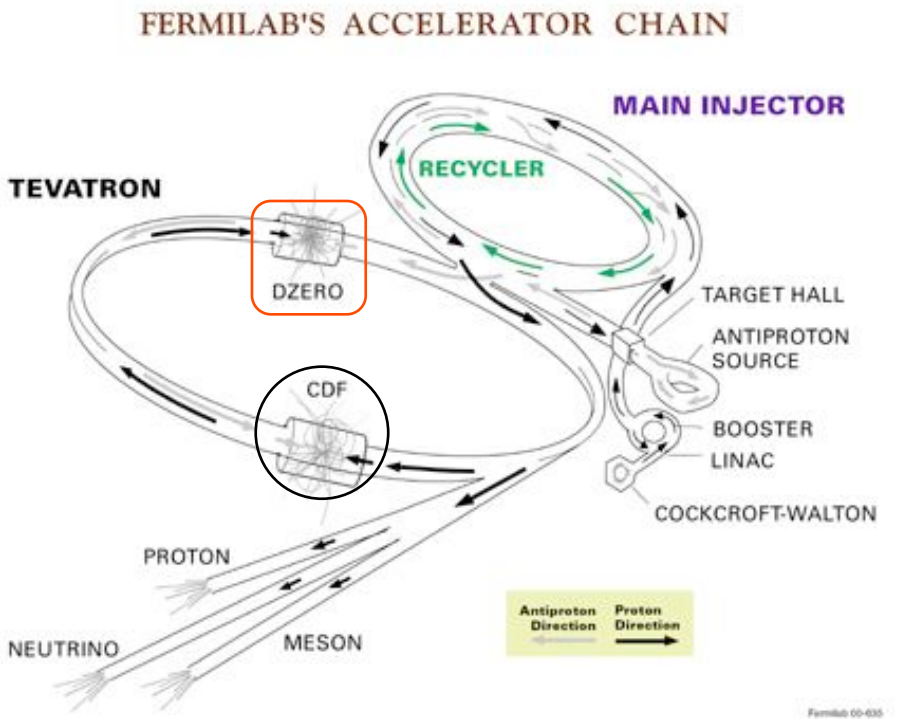
Outline

- Introduction
- Single photon production measurements
- Photon pair production measurements
- Conclusions

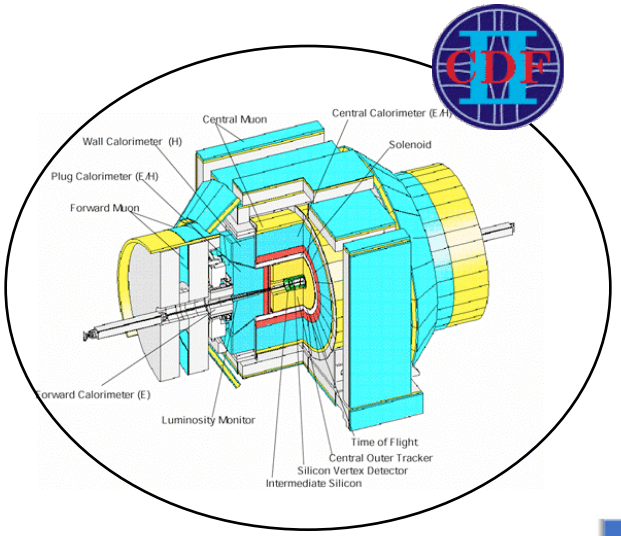
Introduction

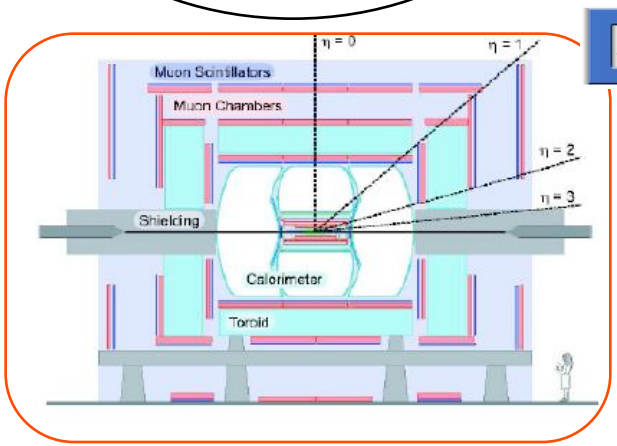
- Direct or prompt photon = not coming from neutral hadron decays (mostly π^0 and η) or from radiation in the detector material — non-prompt photons form a background which is subtracted from the data
- Photons can be measured with **high precision** in modern calorimeters
- Measurements of direct photon differential cross sections are a precision probe for understanding the dynamics of high energy hadron collisions and for searching new phenomena
- The Tevatron is an ideal place to conduct such measurements: A highly performing collider with two **well understood detectors, CDF and D0**, provide a large amount of high quality data

Experimental Environment: Fermilab Tevatron



- ppbar collisions at 1.96 TeV (since 2001)
- ~ 9.5 fb^{-1} delivered, ~ 8 fb^{-1} on tape for each experiment



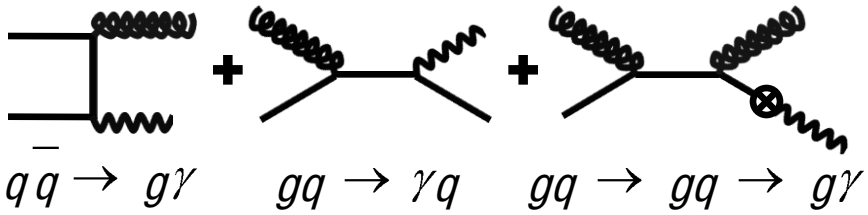


- Central electromagnetic calorimeters
  - → CDF: scintillator – lead with pre-radiation (CPR) and shower profile (CES) chambers
    $\sigma(E)/E = 13.5\%/\sqrt{E} \oplus 1.5\%$
  - → D0: liquid argon – uranium
    $\sigma(E)/E = (18.0 - 20.0)\%/\sqrt{E} \oplus 2.0\%$

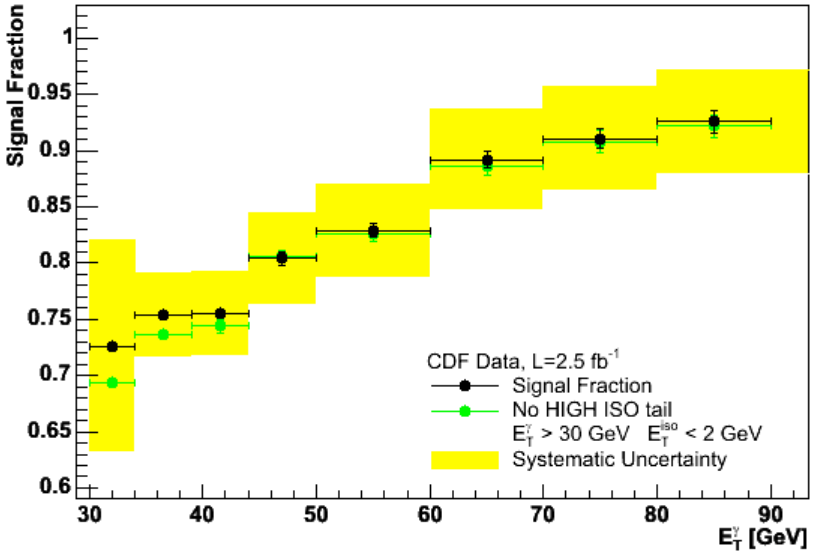
Measurement of the Inclusive Isolated Prompt Photon Cross Section using the CDF Detector

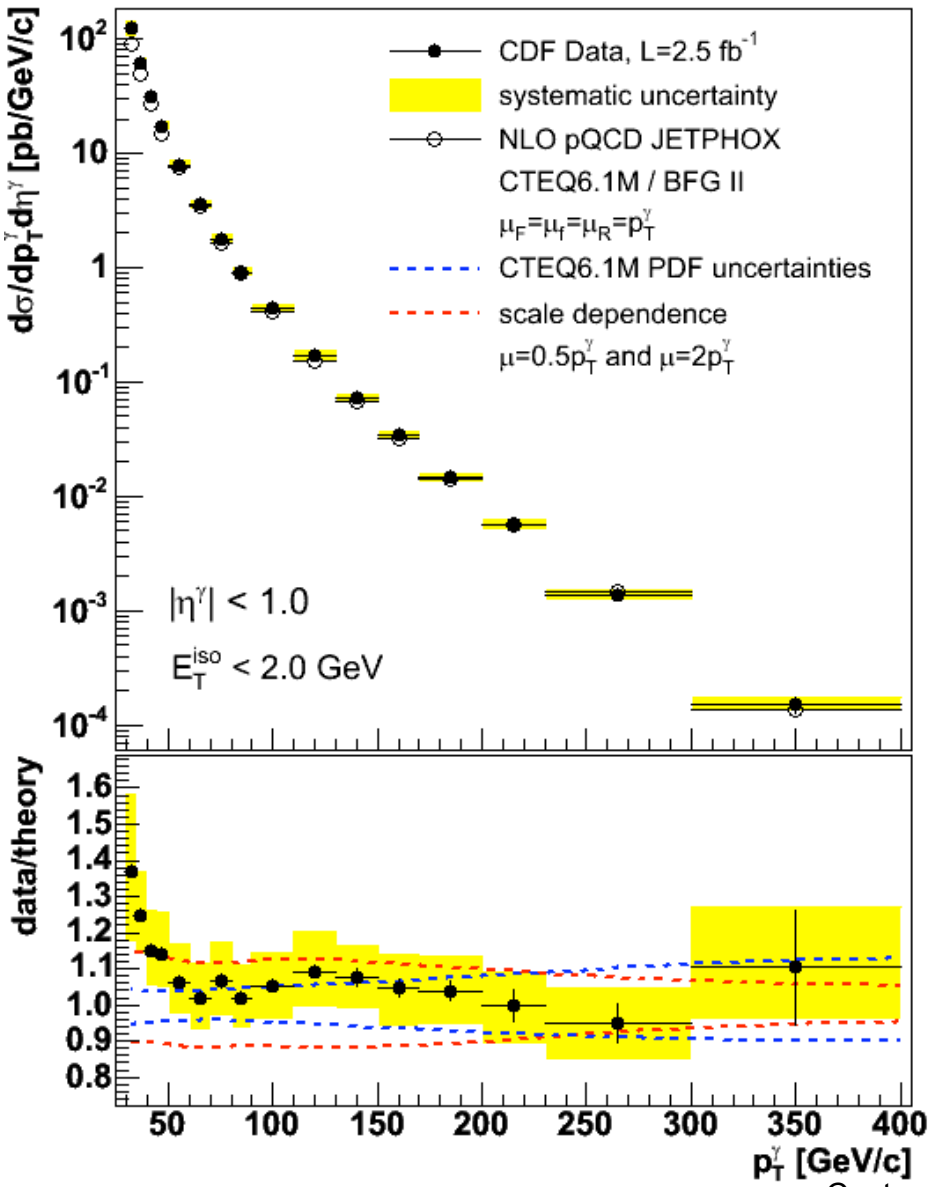
(Phys. Rev. D80: 111106, 2009 arXiv:0910.3623v2)

- Quark annihilation, Compton scattering and quark → photon fragmentation (hard bremsstrahlung from the final state quark) dominate

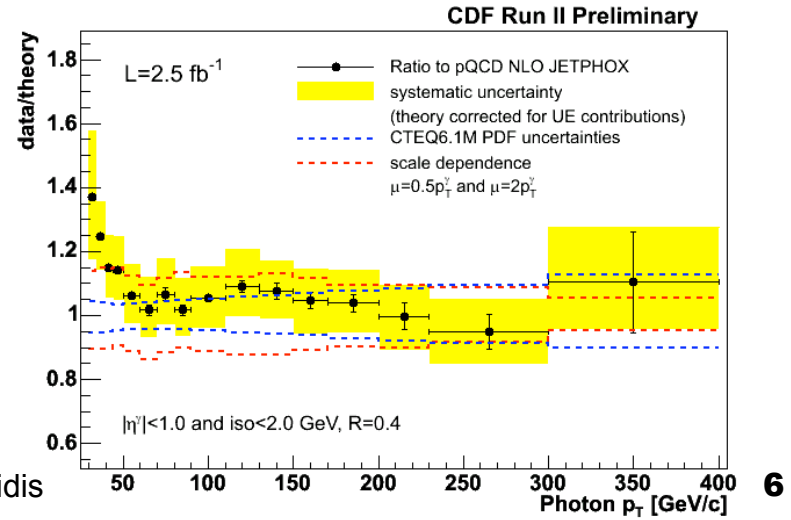


- Measurement of $d\sigma/(dE_T^{\gamma}dy^{\gamma})$ **tests pQCD** with potential to constrain the proton PDFs
- Isolated photons ($E_T^{R=0.4} - E_T^{\gamma} < 2$ GeV) with 30 GeV < E_T^{γ} < 400 GeV and $|y^{\gamma}| < 1$ selected from **2.5 fb^{-1} of data**
- Background is subtracted by fitting **Pythia** γ+jet (for signal) and dijet (for background) templates of the **calorimeter isolation** distribution to the measured distribution in different E_T^{γ} bins





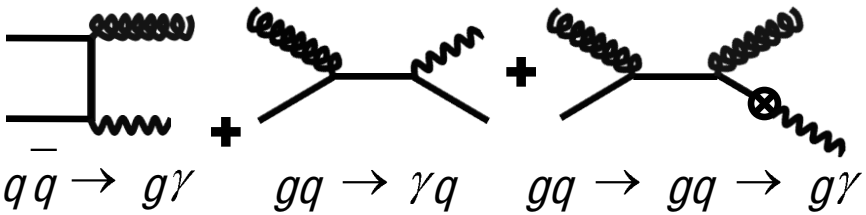
- Dominant sources of systematic uncertainty in data: **signal fraction estimate** at low E_T^γ and **energy scale** (tuned with $Z \rightarrow e^+e^-$ "photon-like" selected events) at high E_T^γ
- Data compared with NLO calculations (**Jetphox**) which include fragmentations [S. Catani *et al.*, JHEP **0205**, 028 (2002)]
- Data & theory in **fair agreement**, within uncertainties, except at low E_T^γ (< 50 GeV, dominated by Compton scattering) where theory underestimates data

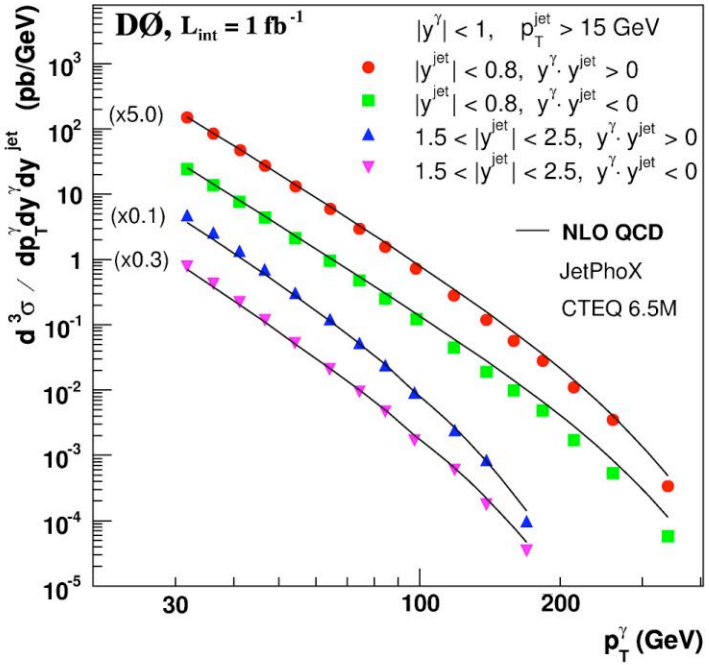


Measurement of the Isolated Photon Cross Section with Associated Jet using the D0 Detector

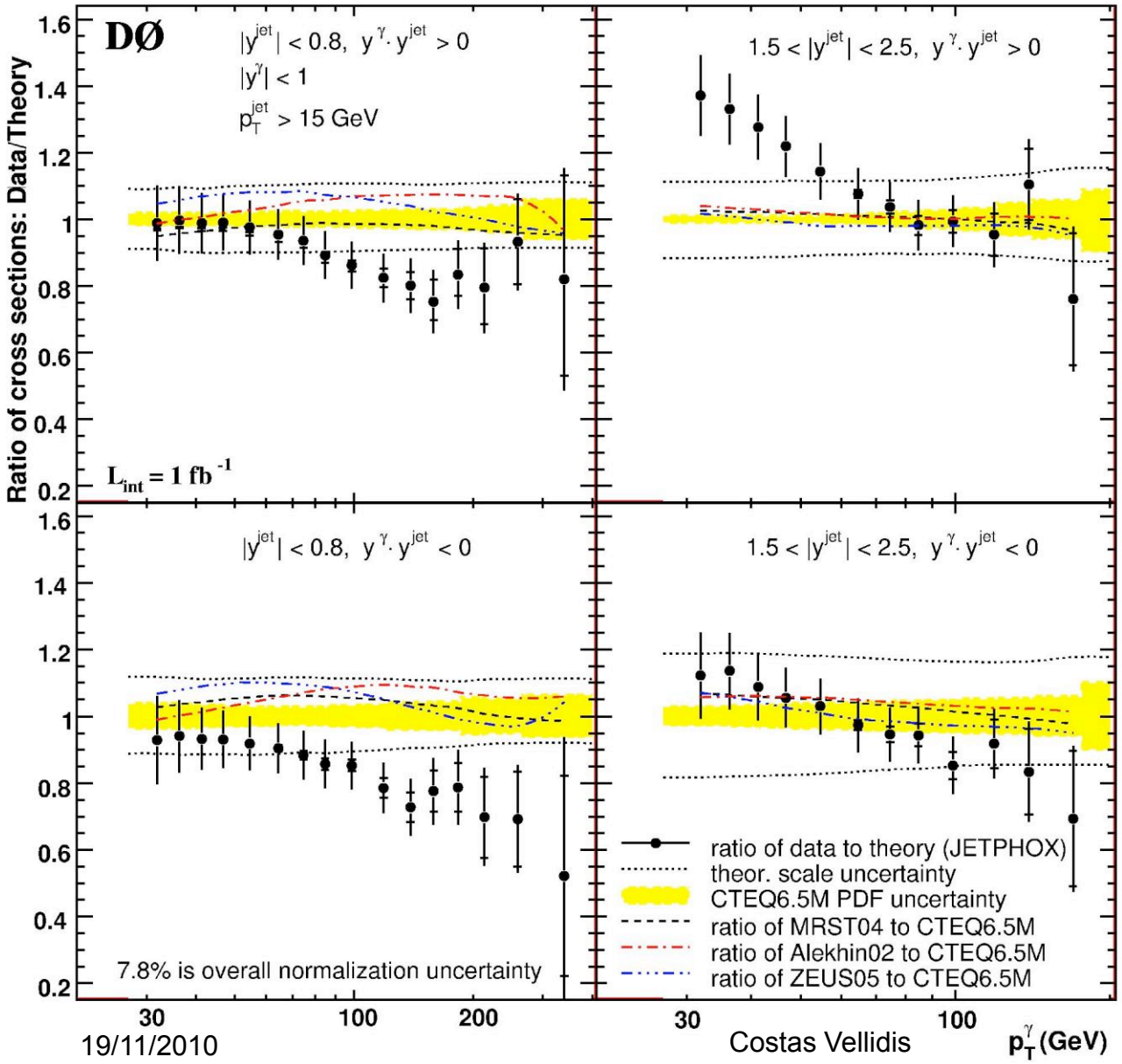
(Phys. Lett. B 666, 2435, 2008 arXiv.org:0804.1107)

- Quark annihilation, Compton scattering and quark → photon fragmentation dominate
- Measurement of $d\sigma/(dE_T^{\gamma}dy^{\gamma}dy^{jet})$ **tests pQCD** with potential to constrain proton PDFs
- Isolated γ's $[(E_{tot}^{R=0.4} - E_{em}^{R=0.2})/ E_{em}^{R=0.2} < 0.07)$ with $E_T^{\gamma} > 30$ GeV and $|y^{\gamma}| < 1$ selected from **1 fb^{-1} of data**
- Background photons subtracted with a **NN**
- **Central** ($|y^{jet}| < 0.8$) and **forward** ($1.5 < |y^{jet}| < 2.5$) jets with $E_T^{jet} > 15$ GeV selected
- Cross sections measured in 4 angular regions





$y^{\gamma}y^{jet} > 0$ (< 0) for central (forward jets) to **separate low and high x** parton scattering

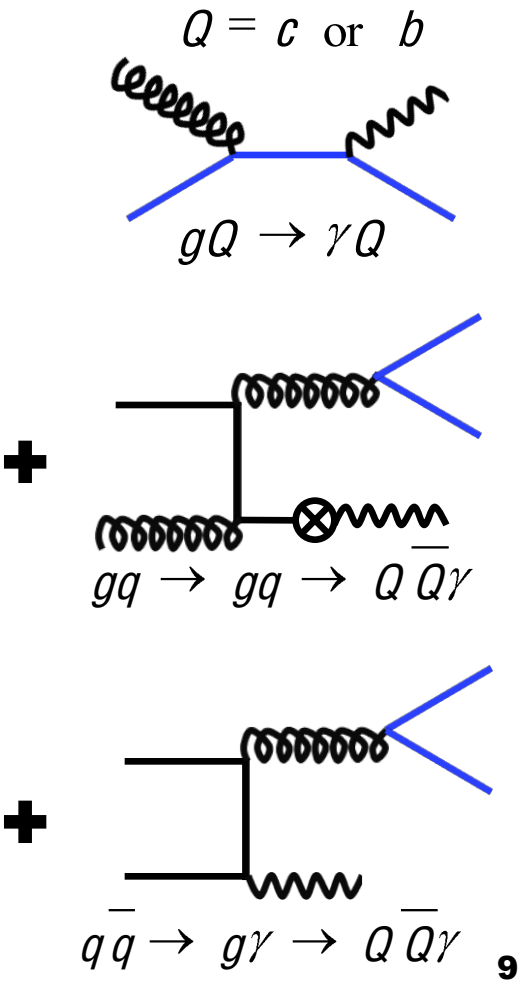


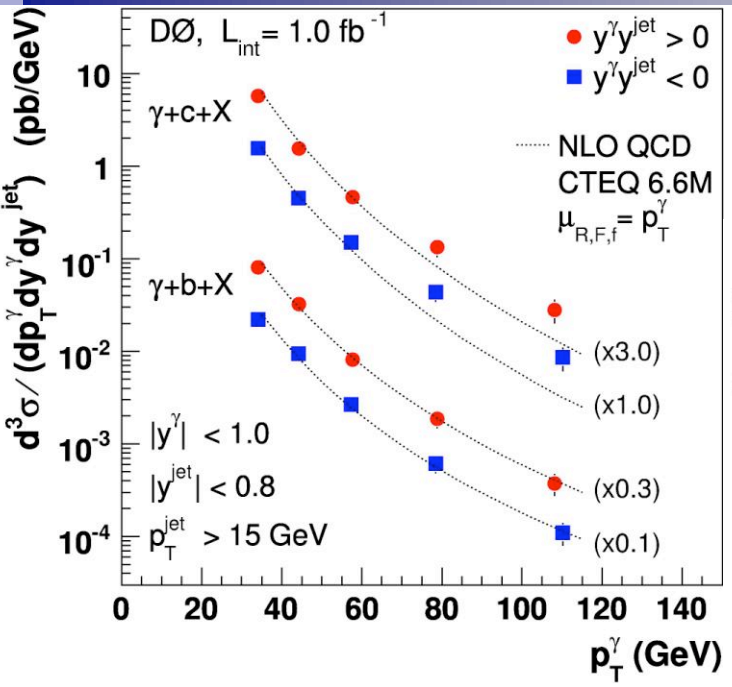
- Data compared with NLO (**Jetphox**) calculations
- Theory **does not describe the data** well enough within uncertainties

Measurement of the Photon Cross Section with Associated Heavy Flavor Jet using the D0 Detector

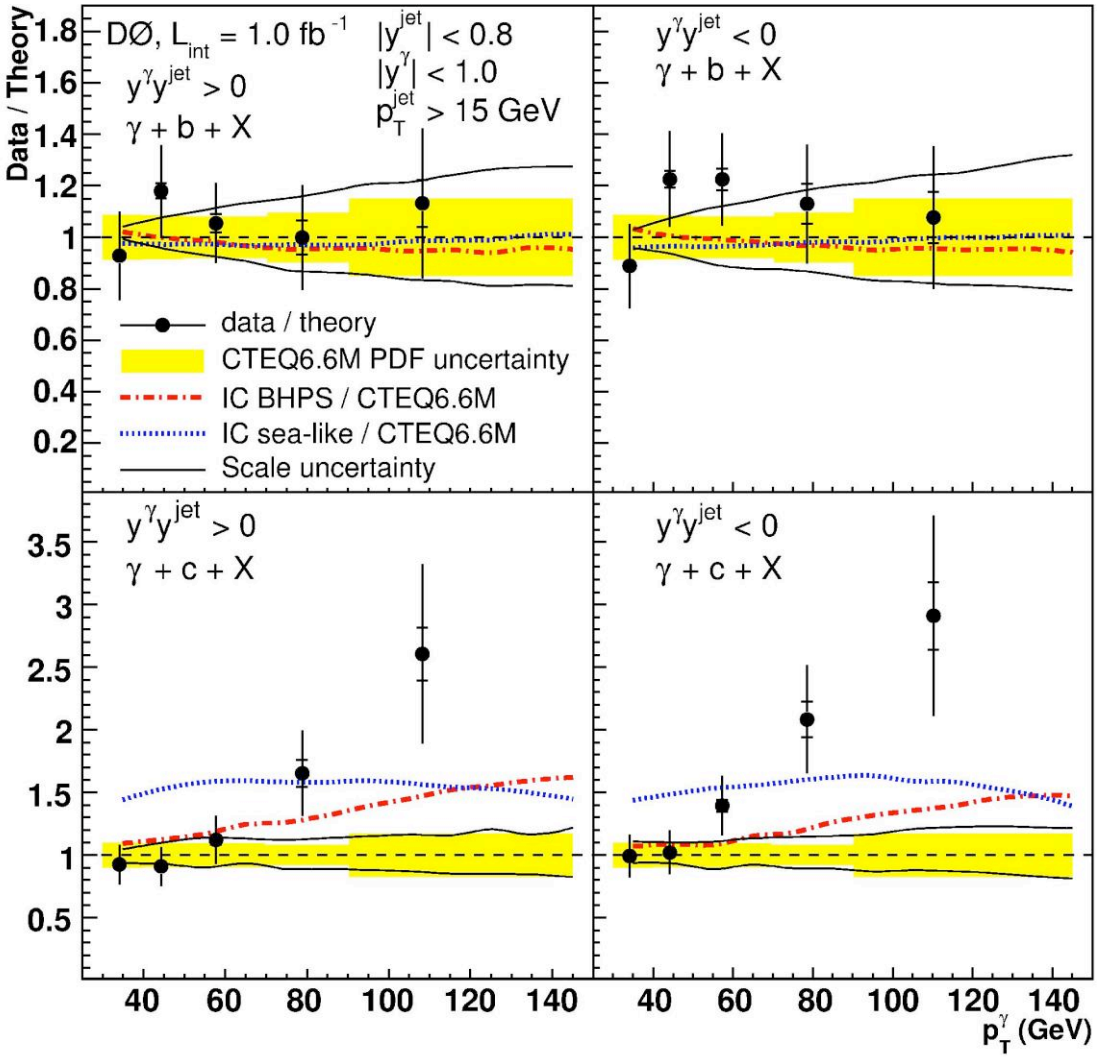
(Phys. Rev. Lett. 102, 192002, 2009 arXiv.org:0901.0739)

- Compton scattering dominates at $E_T^{\gamma} < 90$ (150) GeV for c (b) quarks, quark annihilation contributes too
- Measurement of $d\sigma/(dE_T^{\gamma}dy^{\gamma}dy^{jet})$ **tests the heavy flavor and gluon contents** of the proton
- Isolated γ's $[(E_{tot}^{R=0.4} - E_{em}^{R=0.2})/ E_{em}^{R=0.2} < 0.07)]$ with $E_T^{\gamma} > 30$ GeV and $|y^{\gamma}| < 1$ selected from **1 fb^{-1} of data**
- Background photons subtracted with a **NN**
- Central ($|y^{jet}| < 0.8$) jets with $E_T^{jet} > 15$ GeV selected, heavy flavor tagged using a **NN** based on heavy flavor hadron life times
- γ+LF jet background subtracted by fitting **Pythia templates** compared with negative tag data





Statistical uncertainty in data 2-9%, systematic uncertainty 15-28% with main sources the γ **purity** at low E_T^γ and the **HF fraction** at high E_T^γ



- Data compared with NLO QCD* calculations in 2 angular regions, $y^\gamma y^{jet} > 0$ and < 0

  *[arXiv:0901.3791v1 (2009) & PRD**65**, 094032 (2002]

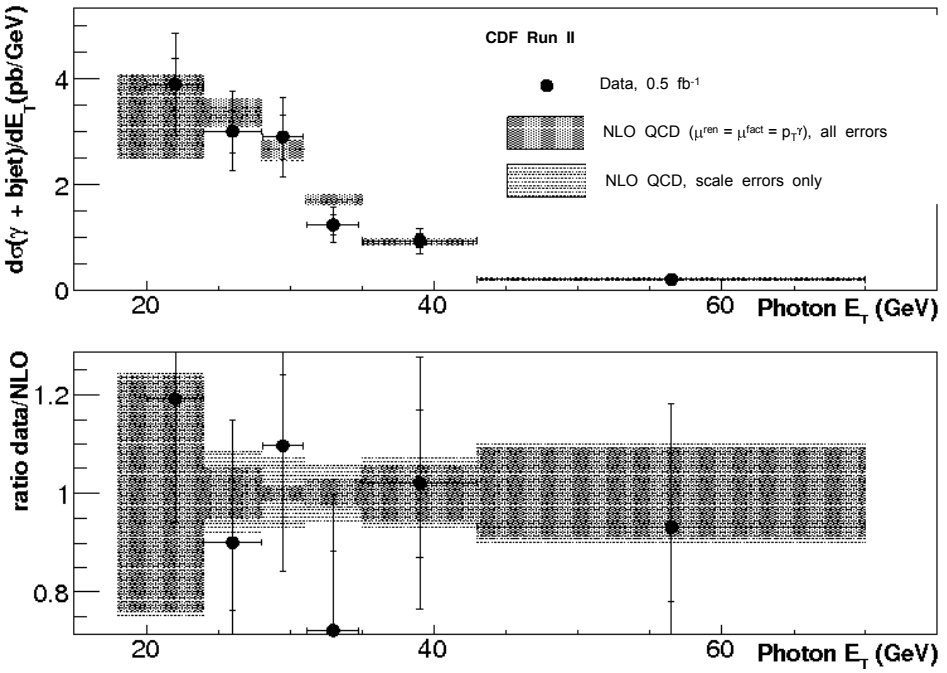
- Theory **agrees with γ+b** data but **not with γ+c** E_T^γ >70 GeV data; adding intrinsic charm (IC) in CTEQ6.6 * tends to correct the predictions

*[PRD**75**, 054029 (2007)]

Measurement of the Photon Cross Section with Associated b Flavor Jet using the CDF Detector

(Phys. Rev. D. 81, 052006, 2010 arXiv:0912.3453)

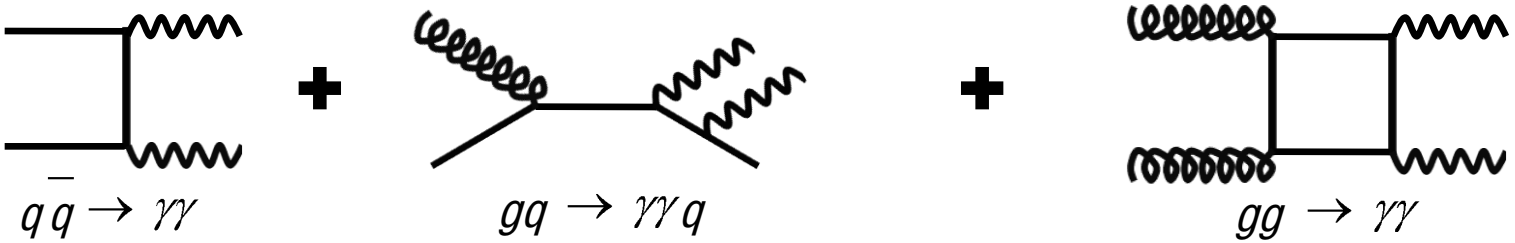
- Isolated γ's ($\Sigma E_T^{R=0.4} - E_T^{\gamma} < 2$ GeV) with $E_T^{\gamma} > 20$ GeV and $|y^{\gamma}| < 1.1$ selected from 0.5 fb^{-1} of data
- Background photons subtracted using **CPR and CES data**
- Central ($|y^{jet}| < 1.5$) jets with $E_T^{jet} > 20$ GeV selected, b jets identified using **secondary vertex displacement**
- γ+LF jet background subtracted by fitting **Pythia** γ+HF jet and γ+LF jet **templates** to the data
- Main source of systematic uncertainty in the data (~17%) is the **b jet purity**



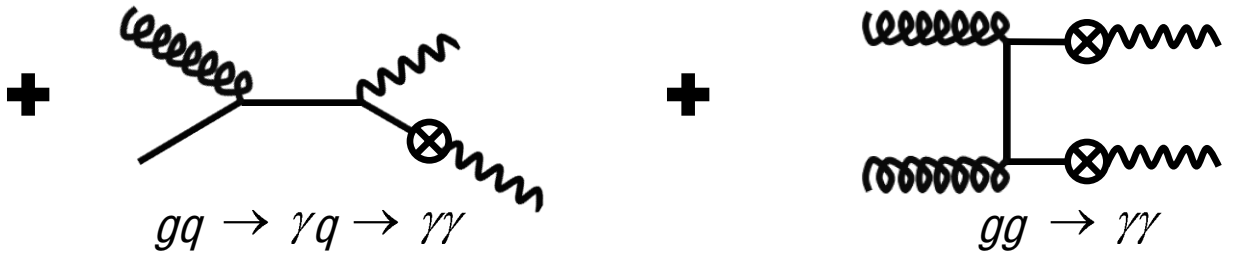
- The data are well described by NLO calculations [PRD **79**, 054017 (2009)]

Direct Photon Pair Production Cross Section

- $\gamma\gamma$ is a search channel for light mass **Higgs and new phenomena** (new heavy resonances, extra spatial dimensions, …); direct $\gamma\gamma$ production is an irreducible background to these searches, need to be understood
- Quark annihilation, gluon fusion and Compton scattering (very small) contribute; fragmentations are also important in the gluon fusion and Compton scattering channels for high gluon luminosity
- Measuring $d\sigma/dX$ $\{X = M_{\gamma\gamma}\ ,\ p_T^{\gamma\gamma}\ ,\ \phi_{\gamma\gamma}\ ,\ \cos\theta_* \cong \tanh[(y_{\gamma 1}-y_{\gamma 2})/2]\}$ **also tests pQCD**



annihilation Compton fusion

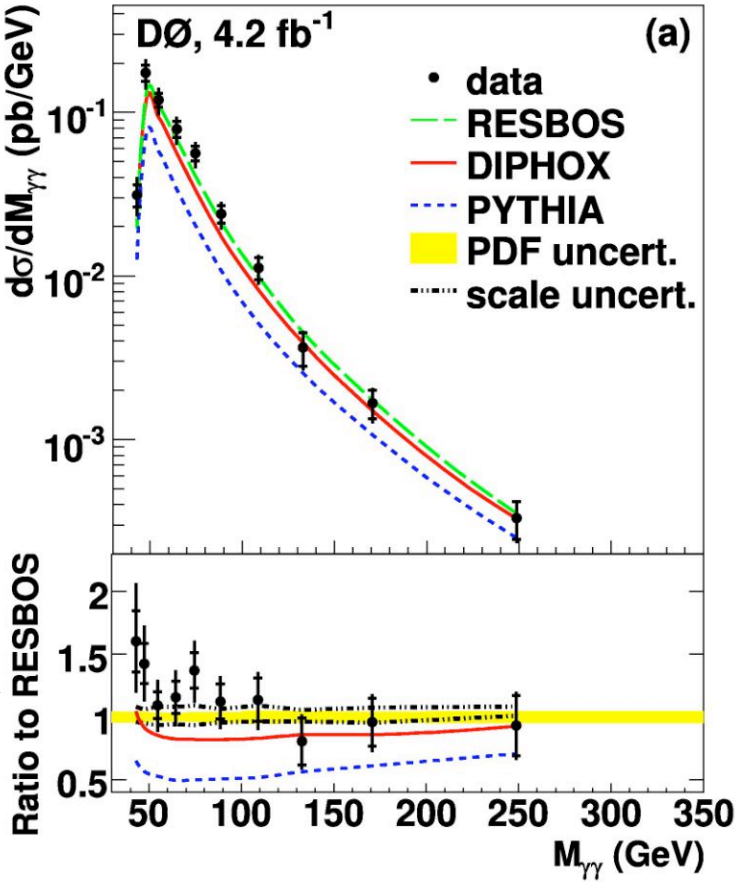


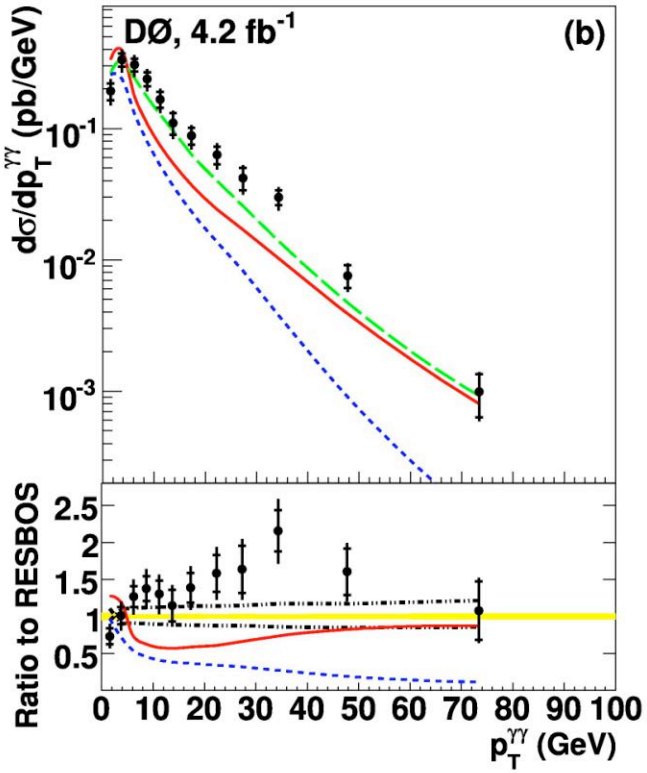
Compton + 1 fragmentation fusion + 2 fragmentations

Measurement of the Direct Photon Pair Production Cross Section using the D0 Detector

(Phys. Lett. B 690, 108, 2010 arXiv.org:1002.4917)

- Isolated γ's $[(E_{tot}^{R=0.4} - E_{em}^{R=0.2})/ E_{em}^{R=0.2} < 0.1]$ with $E_T^{\gamma 1} > 21$ GeV, $E_T^{\gamma 2} > 20$ GeV and $|y^{\gamma}| < 1$ selected from **4.2 fb^{-1} of data**
- Also required $\Delta R > 0.4$ and **$M_{\gamma\gamma} > p_T^{\gamma\gamma}$** which, together with the isolation cut, eliminate most of the fragmentation contributions
- Small background from **$Z \rightarrow e^+e^-$** events faking $\gamma\gamma$ subtracted using a **Pythia** $Z \rightarrow e^+e^-$ sample normalized to the NNLO $Z \rightarrow e^+e^-$ cross section
- Diphoton background subtracted with a 4×4 matrix technique using a **NN** output as the discriminant between signal and background photons
- Single- & double-differential cross sections were measured

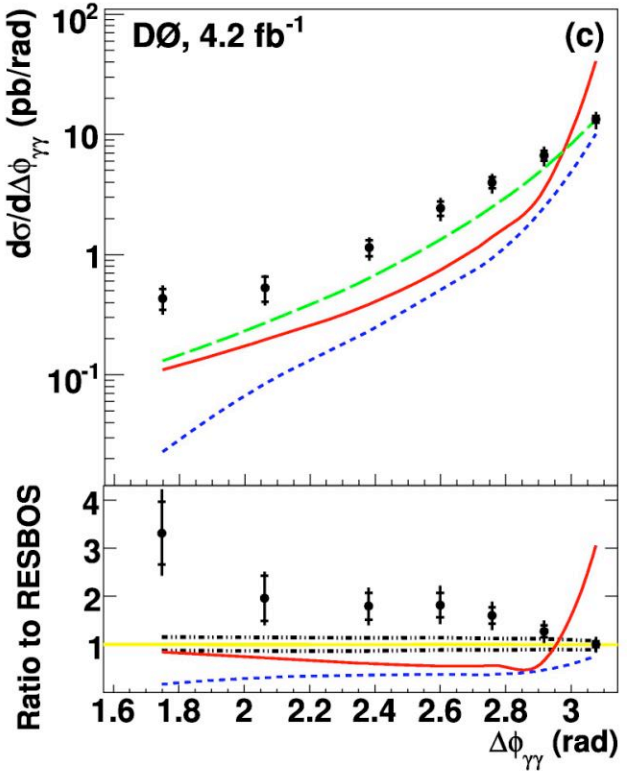




Data are compared with calculations from

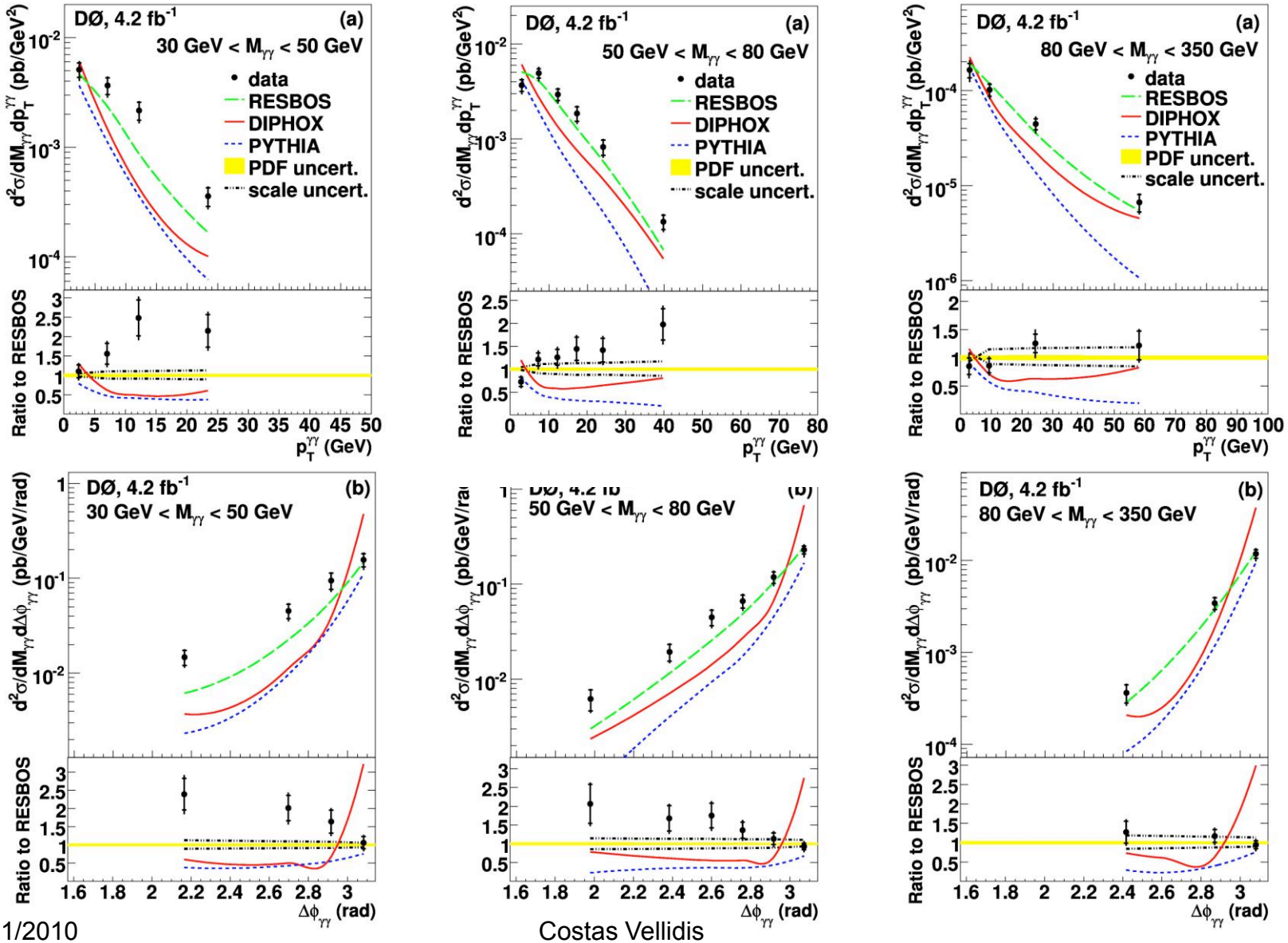
- **Pythia*** [LO + underlying event]
- **Diphox**** [NLO + fragmentations]
- **Resbos***** [NLO + soft gluon resummation]

*JHEP **0605**, 026 (2006); **Eur. Phys. J. C**16**, 311 (2000); ***PRD**76**, 013009 (2007)



- NLO cross sections **corrected** for multiple interactions & hadronization derived from **Pythia**
- **None of the 3 predictions describes the data** well over the full kinematic ranges
- NLO **performs well** at high $M_{\gamma\gamma}$, low $p_T^{\gamma\gamma}$, large $\Delta\phi_{\gamma\gamma}$, the range of Higgs & new physics searches
- **Sherpa*** calculations [Tree-level matrix element + parton showering] describe D0 results quite well (F. Siegert, http://omnibus.uni-freiburg.de/~fs1015/talks/2010-05-CMS-Hgg.pdf)

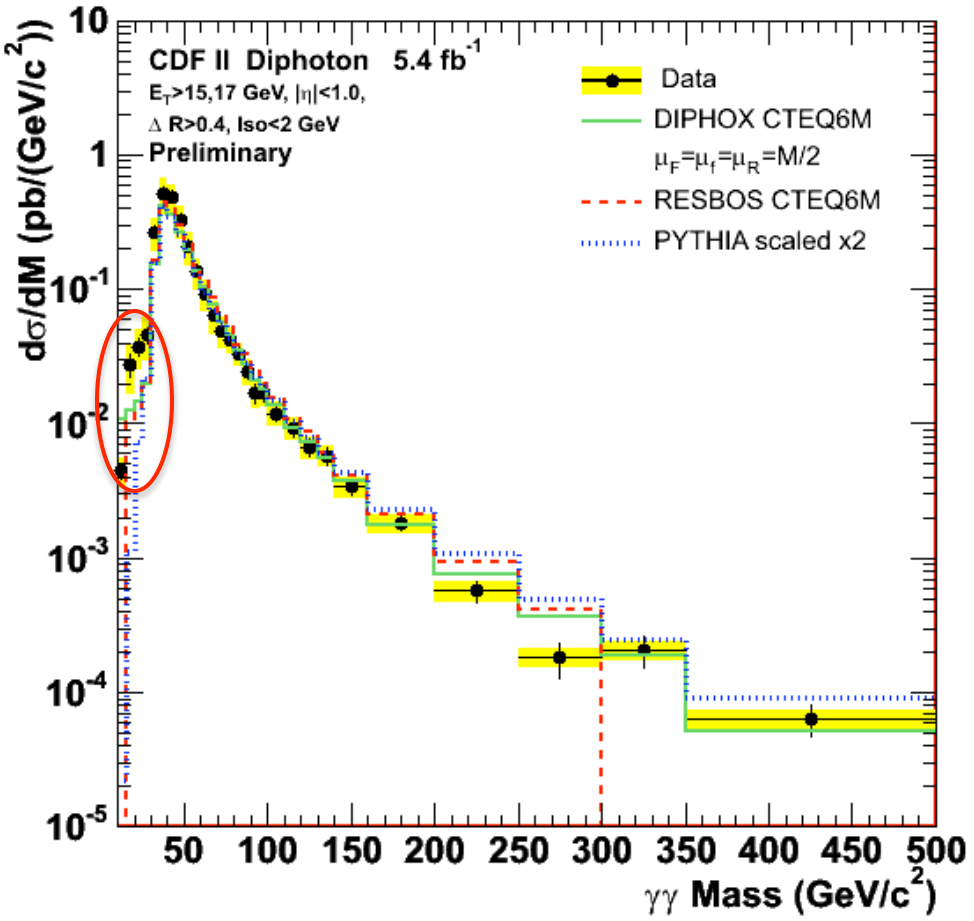
Direct Photon Pair Production Double-differential Cross Sections measured with the D0 Detector

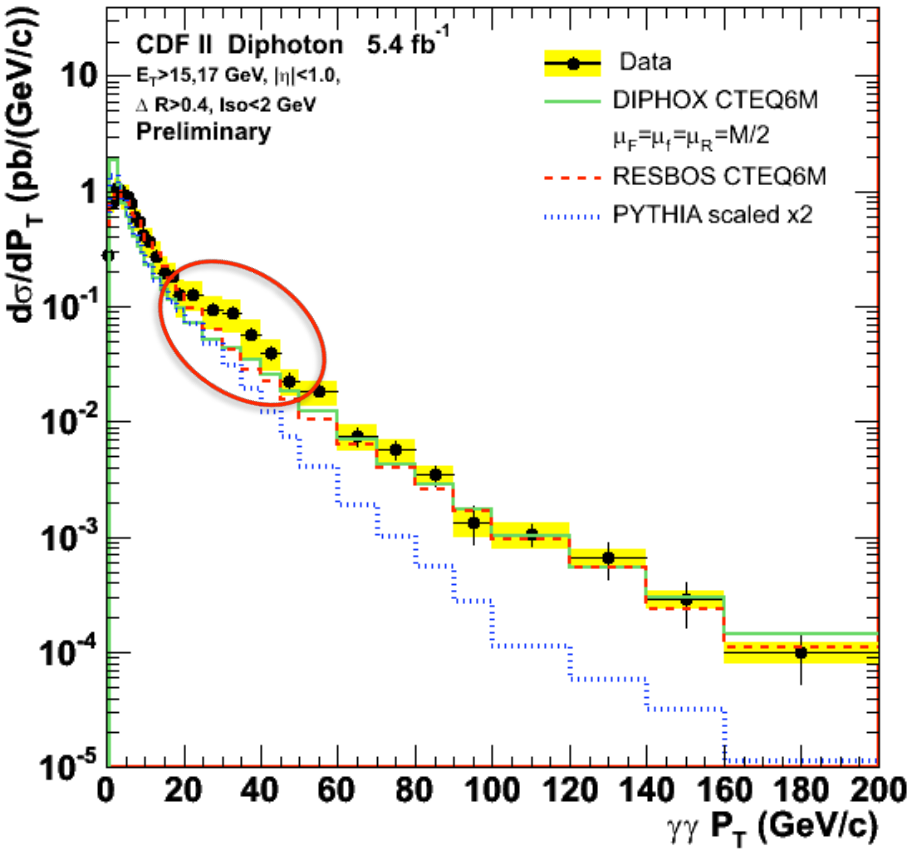


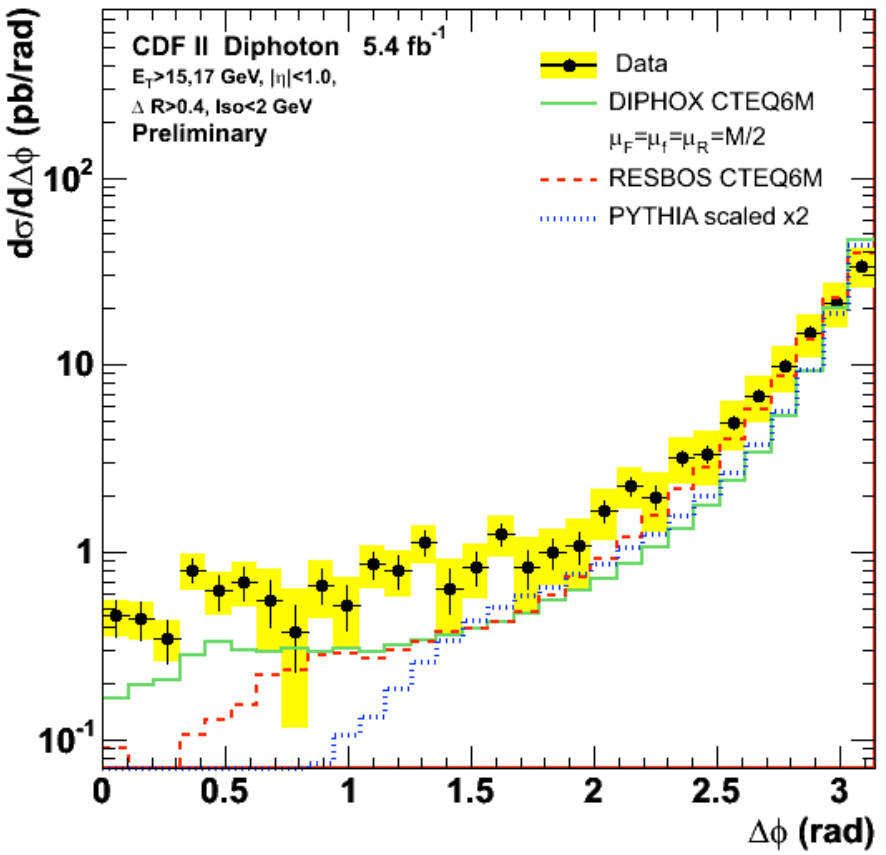
Measurement of the Direct Photon Pair Production Cross Section using the CDF Detector

(www-cdf.fnal.gov/physics/new/qcd/diphXsec_2010/public_diphoton.html)

- Isolated photons ($\Sigma E_T^{R=0.4} - E_T^{\gamma} < 2$ GeV) with $E_T^{\gamma 1} > 17$ GeV, $E_T^{\gamma 2} > 15$ GeV and $|y^{\gamma}| < 1$ selected from **5.4 fb^{-1} of data**
- Diphoton background subtracted with a 4×4 matrix technique using the **track isolation** ($\Sigma p_T^{R=0.4} - p_T^{\gamma}$) as the discriminant between signal and background photons
- Data are compared with calculations from **Pythia**, **Diphox** and **Resbos**

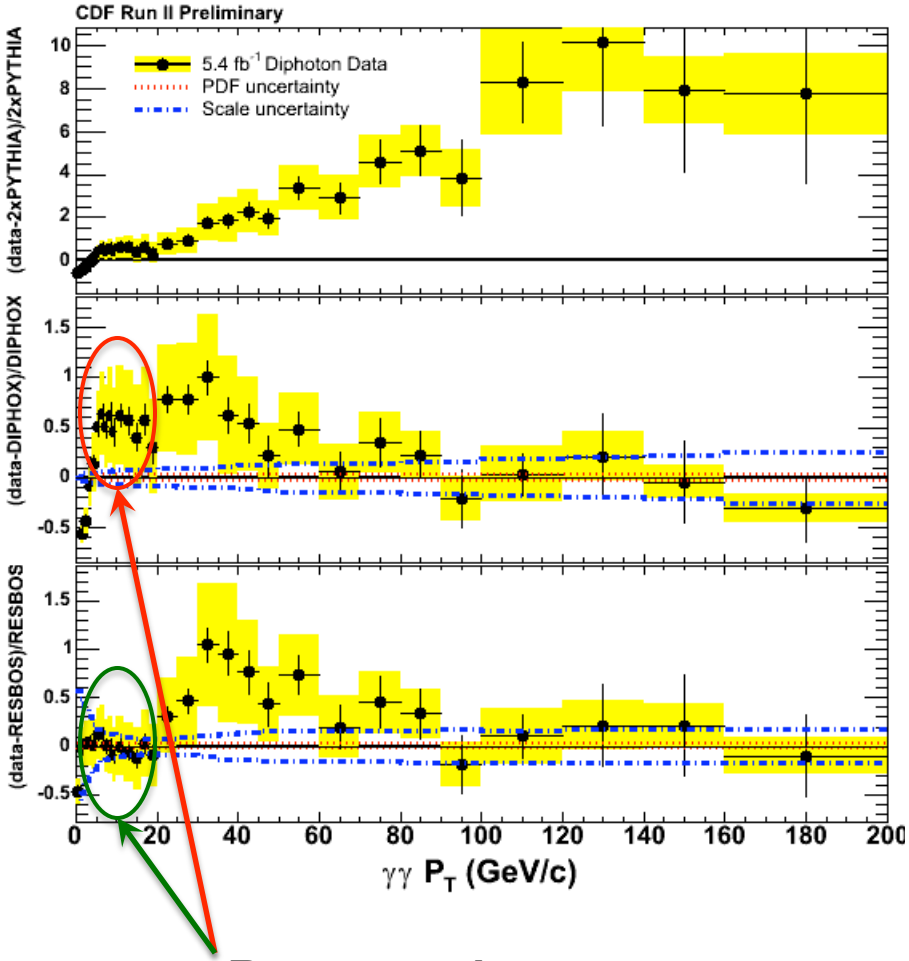




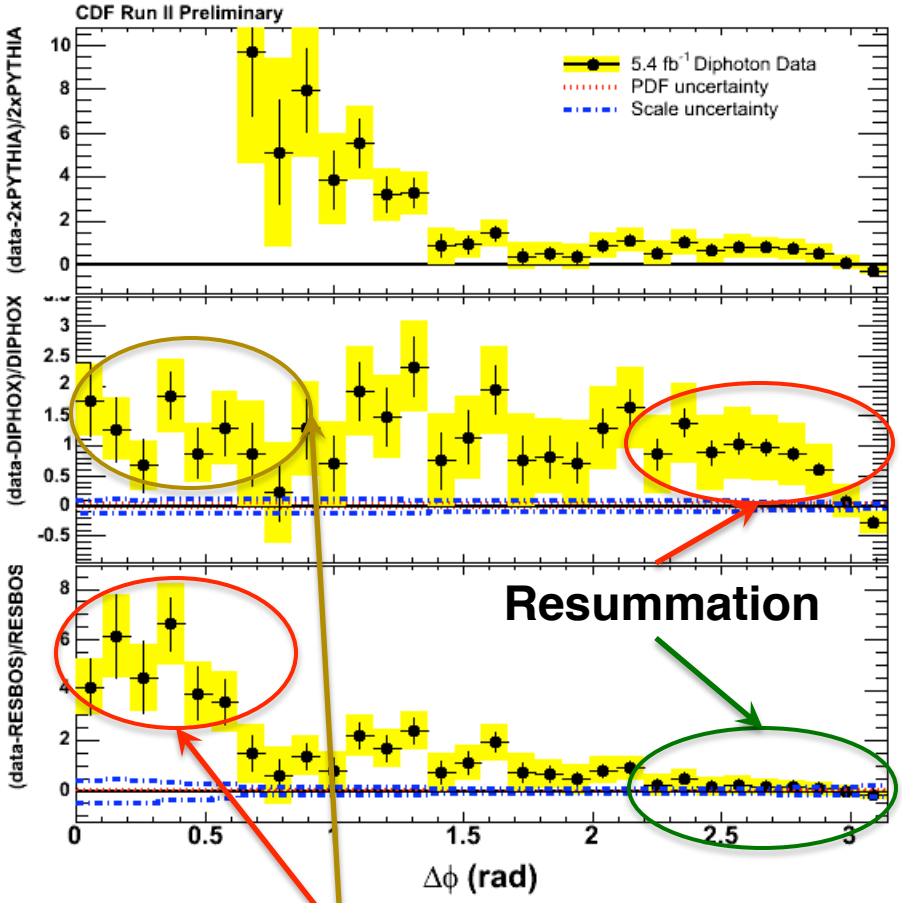


- **No model describes** the data well over the full kinematic ranges, in particular at **low** $M_{\gamma\gamma}$ (< 60 GeV/c^2), moderate $p_T^{\gamma\gamma}$ (20 – 50 GeV/c) and **low** $\Delta\phi_{\gamma\gamma}$ (< 1.7 rad) where fragmentations are expected to contribute signifcantly

Direct Photon Pair Production Differential Cross Sections measured with the CDF Detector: Ratios of Data/Theories



Resummation



Fragmentations

Conclusions

- **High precision measurements** of direct photon differential cross sections over **wide kinematic ranges** have been recently published, or will be published soon, from the Tevatron
- **Single direct photon** cross sections have been measured for
  - inclusive production
  - light flavor jet-associated production
  - heavy flavor jet-associated production

  NLO pQCD calculations **do not describe well the jet-associated production**, in particular for charm flavored jets
- **Direct photon pair** cross sections have been measured
  - **Overall agreement** between data and theory,within known limitations, observed
  - **Resummation** matched with NLO pQCD calculations **works well** at low $p_T^{\gamma\gamma}$ ($\leq$ 20 GeV/c) and large $\Delta\phi_{\gamma\gamma}$ ($\geq$ 2.2 rad)
  - **Fragmentations** appear to be **not under good control** in sensitive regions ($M_{\gamma\gamma} \leq 60$ GeV/c^2, 20 GeV/c $\leq p_T^{\gamma\gamma} \leq$ 50 GeV/c, $\Delta\phi_{\gamma\gamma} \leq 1.7$ rad)